

# GRAPHS, SETS AND COVERS; SEEING WHAT HAS ALWAYS BEEN THERE: Finding Common Ground between BIM Applications and their Users

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**Abstract:** Building Information Models and Process Diagrams rely on data modeling types that can vary. By definition, information contained in the very common Relational Model Databases (RMDDB) can be contained in the GDBs; by expressing relations as tuples enriched with attributes. Also, other Data Modeling paradigms more specifically explored in the Architecture, Engineering, and Construction (AEC) realm, such as (Extended) Entity Relationship Models (EER), Object Role Models (ORM) are already structured as networks. This makes their direct transfer to GDBs possible, while maintaining functionalities such as “attribute sets” in querying the resulting structures through clustering.

Graph Databases (GDB) are database architectures structured to permit network analysis methods on structured data. These databases are built using graph structures comprised of Nodes, Edges, and Properties (Labels or Attributes). These structures can be explored with semantic queries while storing data in an inter-related manner.

In the Process Modeling domain, common methods of rigorous communication, such as BPMN or UML—and its more engineering focused subset SysML, derive their validation and semantic execution capabilities thanks to their directed network structure. Again, making it possible to transfer native process model information to GDBs.

While these structures can be observed in information models related to building and design practice, in this paper we want to extend the Network Model towards the cognitive processes that are part of design and engineering, to this end World Graph (WG) theory, a metaphysical framework. (Dipert, 1997) WG provides a scaffolding to lay out the interactions between cognitive and motivational states that are part of the decision making.

Within this context, attention is given to Small World Networks, which are graphs that can be used to represent frequently encountered problem spaces. A caveat is, that AEC information spaces can present themselves very scattered overall, while tightly clustered within different expertise domains, e.g., paneling dependent on very intricate hardware of many low tolerance components; or material differences in common building methods, such as RC detailing. This is why we believe SWN models can be good candidates for structuring cross domain relationships in a process and object oriented AEC workflow bridging the gap between human cognition and Building Information Models, using rigorous methods, tried and tested in the realm of network science and graph theory.

To this end we will demonstrate Graph mappings of design parameters (affordances, objectives, etc.), material properties (ductility, weight, etc.), logistics (order, transportation, etc.), and fabrication methods (shaping, fitting, etc.) tracing a contiguous network between expertise domains, as a proof of concept for developing a common modeling environment between human understanding, communication and storage tools in AEC problem spaces.

**Keywords:** Semantic web, IFC, graph databases, design cognition, process model

## INTRODUCTION

Building information modeling (BIM) processes are collections of various tools, methods, legal and information schemata aimed at creating digital environments for creation, management and storage of representations of diverse elements such as, physical spaces, material properties and scheduling arrangements regarding the built world.

The results of this process is generally a BIM repository that contains data regarding assets in a structured manner. Thanks to the ready availability of information from different expert domains and many

aspects of building operations; users can extract, exchange, or derive information without separate Requests For Information (RFI) that are common causes for communication errors and delays in Architecture, Engineering and Construction (AEC) workflows.

Currently most Building information models (BIMs) are stored in proprietary file formats and there is a push from the software industry to offer BIM services such as hosting and access control on remote servers and within proprietary frameworks (BIM360, Procore, Bluebeam etc.).

Within this context most products have their own internal structure to organize project related data, building object classifications and even different geometry modeling kernels. This makes interoperability and standardization a challenge onto itself.

BuildingSMART is the international body that has developed Industry Foundation Classes (IFC), the most widely adopted and open interoperability format. IFC is also a registered standard by International Organization for Standardization under ISO 16739-1:2018.

A further observation to be made is that while topological connectivity information is generally present while drafting in a BIM Suite, much like geometric constraint satisfaction and, the analytic computer graphics solutions that are at the core of user interfaces, most of this information is not transferred outside of their initial realms.

### 1. IFC, SEMANTIC WEB AND ATOMIC GRAPHS

IFC provides an Entity-Relationship (ER) model that supports validation and is based on EXPRESS data modeling language, the ISO standard for Product Exchange models (STEP ISO:10303-11:2004). The structure of an EXPRESS, thus IFC, model is of a networked nature. EXPRESS model schema is a plain text file that presents itself as a series of separate lines using Wirth syntax notation (WSN) (Wirth 1977). Limited to a subset of Unicode Basic Latin Block, it incorporates three commands from the C0 control stack, supplemented with a newline special command “\n”. This straightforward and barebones approach lets EXPRESS be readable by humans and by computers for validation, and host various aspects of “the diverse material addressed by ISO 10303” (STEP ISO:10303-21). Within this frame, EXPRESS language focuses on definition of entities with properties and constraints. EXPRESS is context neutral, can host multiple data type definitions with their own algorithmic rules, and supports specification of models for specific views.

While EXPRESS is the primary schema adopted for IFC, different research efforts are underway for representing the relation-network information present in IFC through other schemata. Web Ontology Language (OWL) and Resource Description Framework (RDFs) or Extensible Markup Language (XML) and XML Schema (XSD), which are data modeling approaches for Semantic Web and the Internet developed and standardized by World Wide Web Consortium (W3C) are considered equal alternatives to EXPRESS-IFC by BuildingSMART under the names of ifcOWL and aecXML.

XML-XSD and OWL-RDF are tools that have been developed for data exchanges outside the realm of AEC. Both establish machine readability for content as a prime goal. While XML states the intent of being human

readable, the level of cognitive permeability changes from context and implementation; likewise, OWL-RDF with different syntaxes and serialization formats offer differing degrees of human readability. By specification, Semantic Web foresees machine readability of the World Wide Web through enrichment with structuring. While large scale implementation over the internet of Semantic Web is still a future aspiration, specific domain applications are already implemented and in use.

In the following section, RDFs with their “subject-predicate-object” type structure handle triples as atomic entities for codifying semantic data. This atomic component presents the smallest Directed Acyclic Graph (DAG), that is a directed relation through predicate between the subject and object. This entails that by forming relationships in this manner while the basic building block remains relational, we can construct Graph Structures for data representation.

The standard query language for RDFs is “SPARQL Protocol and RDF Query Language” that provides NoSQL methods and graph traversal syntax. Furthermore, SPARQL has also implementations that support both relational (Apache Marmotta, etc.) and graph databases. (Amazon Neptune, Oracle Spatial & Graph, etc.)

Triplestores can also be expanded to include more information through layering to satisfy descriptions for more complex information. Such as Molly->IS->Cat; Molly->WATCHES->(Squirrels-IN->The Backyard). The predicate can take more than one target: Molly->IS->(Cat, Tabby). The triples can also be named thus becoming “quadstores” or named graphs. Molly->IS->Cat can be identified as natureOfMolly and can be stored as a quad consisting of <subject>, <predicate>, <object>, <graphName>. More specifically, these names are Uniform Resource Identifiers (URIs) or Uniform Resource Names (URNs). Using named graphs and layering we can extend the type of graphs we define to directed multigraphs (allowing loops) and define hyperedges (connecting more than one vertex).

Each relation defined in an IFC can thus be hosted in this type of relationship and ifcOWL (Pauwels, & Terkaj 2016) that uses OWL instead of EXPRESS schema. This has been implemented in various tools and can be used to infer information to use in concert with Linked Data (LD) or, in particular, Linked Open Data (LOD) that is adopted by several governments across the globe (Holm et al., 2012). OWL can maintain the well detailed and conventional IFC standards for representing construction data, while expanding the capabilities of data distribution, extensibility, reasoning and knowledge inference. ifcOWL also permits validators that are key for BIM standards as can IFC-EXPRESS and aecXML. Also, some Business Process Models that will be discussed further have similar validation capabilities

due to their linked nature. One notable advantage of OWL over EXPRESS is a wider semantic lexicon than basic EXPRESS schema without use of specific Model View Definitions (MVDs).

## 2. GRAPH DATABASES

Relinquishing the atomic structure of Triplestores, we have the option of branching out into the realm of Graph Databases. Graphs, in the broadest sense, are structures that are comprised of a set of discrete elements (vertices) and a set of tuples that establish relationships (edges) between them  $G = (V, E)$ . GDBs, which use graph structures to store and organize data, are again NoSQL databases that present a networked structure. Different than the RDF-OWL approach, GDBs organize the data in a graph of nodes, edges and properties, instead of relying on atomic sentences. As an approach to data modeling, these are akin to the natural view of ER models; as every data element is an explicit entity with types and the relationships between these, are expressed as entities in their own right (Chen 1976).

The elements themselves can have pointers associated instead of having to cite URIs. In a more abstract manner, every element contains pointers to their adjacent element, doing away with the need for index lookups typical of relational databases. This latter property, opens many interesting possibilities as it permits localized solutions on building element interactions on models in contrast to serial ones. In previous research (Bermek, Gentry, and Shelden 2019), we have proposed graph database layers to include proximity information for encoding spatial and material information parsed from IFC files. This was intended for creating robust, cross domain, and rule-based reasoners for Cross Laminated Timber structures.

The property related focus of `IfcArchitecturalDomain` does not necessarily represent structures and connectivity in the IFC file. Rather, if there is a structural model developed within the design process, then IFC provides methods for exporting structural models between structural analysis softwares. While physical element connectivity ontologies are present and key in the `IfcStructuralAnalysisDomain` (since IFC2x), in the architectural domain `IfcRelationship` and its subtypes define relationships between elements of the model. There is no common integration between an object represented in the structural model space with its spatial and assembly constraints and its role as a structural element. That is, the structural domain and the architectural domain serve purposes of interoperability within their respective design realms. This certainly is useful in certain construction types like RC, or steel structures that create a schematic

canvas onto which architectural and system elements are loaded; but does not respond to the nature of construction methods in which the building element has a hybrid role (i.e. masonry, composites, mass engineered timber).

`IfcRelationship` is an abstract generalization of relationships that can have objectified attributes. All the properties are handled at the relationship level and behavior is not directly prescribed while asserting relation. Relying on the Entity Relationship (ER) Model, the relations can be one-to-one and one-to-many but always with a relating and related party.

Among the subtypes of `IfcRelationship`, `IfcRelConnectsWithRealizingElements` can be used to define exteriority relationships, that is to populate an existing model by interstitial elements that establish and reify a connection between disparate elements. This is defined as a ternary relationship. This is a very welcome addition to the IFC4x schema and supersedes the hierarchical nature of relationships defined in previous versions (`IfcRelAggregates`, `IfcRelDecomposes`).

When established, these relationships of exteriority are the key to modeling entities in an adaptive way. As we have underlined when talking about triples, the basic 3 component triple is nothing but a two vertex complete graph ( $K_2: 1$ ) and we can deploy our IFC schema fully using these atomic graphs. The advantage of using a GDB representation for our BIM is thus twofold. For one we can safely accommodate the property-based information that is typical of and IFC file in whichever detail we want. Secondly, we can, through the ternary relation established, populate our geometric model while using other `IfcRelationship` subtypes that define different types of relationships used to model the design space with better fidelity, reliably, and without needing to expand our basic schema (figure 1).

These tools have been covered for outlining the possibility of representing any BIM within a Holistic model, where spatial relationships affecting design, fabrication, or other construction choices can be hosted in its entirety and can be further expanded with secondary property derivation. Property derivation and reasoning are elements on which we will rely heavily (Solihin and Eastman 2015).

Considering:

- How a Graph is a set of vertices associated by a set of tuples that represent connectivity between the vertices, defining relationships (edges),
- Vertices and edges can support labels or properties,
- That the entities, abstract or reified, can be part of different sets within a space (our database),
- Sets of elements themselves can have many associated connectivity sets (multiplex networks),

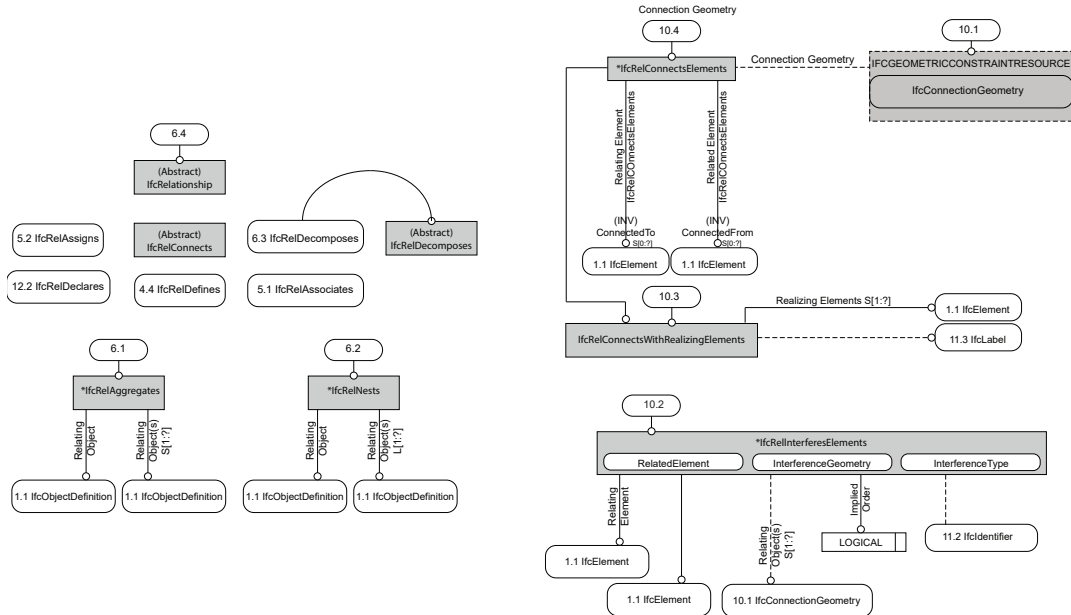


Figure 1: IfcRelationship and subtypes (buildingSMART IFC EXPRESS-G Schema). (Redrawn by the author, 2020)

- We can represent our system and subsystems as a structure of differing complexity: *Assemblages*.

### 3. EXTERIORITY, ASSEMBLAGES AND GRAPHS

Assemblage Theory is a framework first detailed by French philosopher Gilles Deleuze and philosopher and psychoanalyst Félix Guattari in their *A Thousand Plateaus* (2013). The theory provides a scale independent approach that is used for analyzing social phenomena and complexity, putting the changing nature of things in the foreground. This approach derives its essential features from dynamical systems theory, which is the mathematical approach to model chaotic, non-linear, or complex systems. Assemblages assume that parts of a body don't have fixed relationships or interior roles that they are executing within the system; these are rather independent entities that "happen" to be organized in a given manner at a moment in time; their relations are amenable to change. Entities can assume multiple functions and can be replaced or displaced, moving away from an organismic parable of interiority.

These structures—or dispositions—can accommodate self-organization, and conditions that are not intentionally acting on the elements. A common anecdotal example is a ready concrete mix changing properties due to the transit mixer being stuck in traffic or the driver stopping for lunch: A completely unrelated event, changing characteristics of a merely tangent system in a separate domain.

In their discourse Guattari and Deleuze refer to *constellations*. These are a collection of accidentally interrelated properties (cfr. abstract entities) and elements of differing nature. They individuate a plane in which the axes define the level of territorialization and coding. The most coded sectors indicate where matter is most organized around a body. Likewise, the most territorialization is when demarcations become most apparent. Through this particular configuration or form the assemblage composes and establishes a territory.

The apparent hierarchy and stratification of systems is a byproduct of territorialization thus, the vantage point of the observer defines the actual relationship between bodies that can be experienced differently by different actors. Once established, material forms and expressive forms do not remain static, territorialization is a continuous superposition of "build-up, break-down" processes. As an example: while the "construction crew" at the early stages of a building is mostly composed of workers with experience in earthworks, reinforced concrete and formwork, in the later stages of the same project, the composition of the "construction crew" is predominantly carpenters and HVAC technicians. The very workers part of the "crew" at the beginning are possibly part of another project by the moment of delivery. Thus, the transient involvement of any single agent demonstrates the complex manner in which these *assemblages* come into being.

In recent years, philosopher Manuel DeLanda started detailing the concept of assemblages in his 2006 work *A New Philosophy of Society*. His core tenet in expanding the two axes plane into a higher dimension by adding the axis of Genetics-Language (nature-nurture) gives way to dynamic re-coding of the assemblages. While mainly talking about complexity of society in formulating the perceived dynamics and configuration of assemblages, his work has had a profound impact on the study of complexity and geography. DeLanda emphasizes that reality and materiality are independent of their degree of complexity. Concluding that being fluid and mutable in nature and not pinned down to specific components, reading social or material structures as assemblages, does not make these less incisive world altering processes.

As formalized, assemblages at a given moment in time can be represented as a complex, topological network with varying levels of connectivity. These networks can accommodate representations of processes involved in AEC workflows with high levels of detail as they are theoretically multi-scale structures that represent different aspects within the same model. While the nature of the network graph would permit a possibly infinite amount of information to be represented due to its ontology, in practice the capabilities would be limited by the breadth of our *semantic lexicon*, storage, and computation capacity. Notwithstanding these practical considerations the unified representations of "the totality of the building process" would generate models and simulations of currently unachieved levels of detail and power. The vision of a possible model has already inspired different levels of characterization of BIM models. Current state of the art is referencing 7D BIMs as models capable of supporting building asset management life cycle.

Scale-free networks are networks characterized by edge numbers that have a distribution according to power law. These are different than totally random maps as they foresee a diversification between node degrees. That is, having a given number of nodes that have a notably higher degree (number of associated edges) than others. With the degree distribution of the nodes following a Pareto distribution—or the power law—with long trailing ends. Social Networks and, more importantly for our case, Collaboration Models are prime examples of this type of network. The generative processes behind these kinds of networks exhibit preferential attachment stemming from a fitness model. This is to say, stronger elements in a system have more effect in further configuration of their network. Real world examples of these networks represent the *Matthew Effect*, or the "rich get richer" or "success breeds success" dynamic as can be seen in the

distribution of citations of scientific publications, or web page and media click counts. (van de Rijt, Kang, Restivo, and Patil 2014) This tendency becomes relevant to our case in questions regarding continuity of technological systems, and tracing of loads through a structure.

Finally, a strictly related network topology is the small-world network that is defined by degrees of separation. These scale-free networks, as will be mentioned in our main focus, are very-small (or ultra-small) world networks. In scale-free networks, distances between nodes can be  $\log(\log(n))$  whereas in random graphs (or Erdos-Renyi graphs) distances converge towards  $\log(n)$ . (Strogatz, Watts 1998) (Cohen, Havlin 2003)

The small World Hypothesis formulated in 1929 by Hungarian writer Frigyes Karinthy, better known as "six degrees of separation," has been the subject of research throughout the 20th century. Watts and Strogatz 1998 state that, with the addition of only a limited number of wide spanning edges, a regular graph can become a "small world network," where the growth of average number of edges between two given nodes is much smaller than the growth of the size of the network. This is to say that in small-worldness most nodes are not neighbors of each other, but require a small number of steps to reach each other. This property is suitable for optimized human brain networks, reducing energy and dendritic process lengths.

As presented, a networked representation of components of complex systems can yield a higher fidelity model than arbitrary subdivisions and reductionist tabulations typical of a top down, one-size-fits-all standardizations. As a fragmented and static encoding of information about a system that is undergoing shaping, it is not able to convey a contiguous idea of wholeness. This is especially inconvenient regarding the engagement of actors with the process of design.

#### 4. DESIGN DOMAINS AND LOSS OF CONTINUITY

Thought processes and information requirements for design, procurement, fabrication, and assembly can be extremely complex to encode or comprehend with a single language or through a single lens. Different actors are going to approach the same object, treat the same process differently, have conflicting ideas, and supersede decisions made in different stages.

Every item in a complex system can be represented as a stratification subsystem with varying degrees of interaction among themselves. We have seen these in the emergence of assemblages, or as substructures in Dipert's WG. In dealing with the scales involved in design, manufacturing, and AEC workflows, these subsystems can be exemplified by tangible objects or shared conventions in an intuitive manner. Where interactions are dictated not only by spatial

proximity, but also agent and organization based rules: for example when the painter who is going to apply the actual pigment in a room has less effect on the color of the walls than an e-mail exchange between the contractor and the interior designer. The only reason the project coordinator will be informed will be due to coercive form filling requirements borrowed from corporate practices where liability rules supreme and every actor is as alienated from design exploration, as the painter is from their labor. For lack of an adaptive design-planning-building medium.

In the AEC field there are communication systems and calcified roles that are pervasive. These govern the nature of the information transmission and decision making within process and agent interactions involved in delivery of product. It would be beyond the capability of any single innovation to change the way we build. Even suggesting a disruption of traditional hierarchies would probably generate more interest than genuine change. Yet as the nature of our buildings become increasingly complex, the life-cycles for buildings and functions therein imagined are ever more interconnected. This complexity generates novel resources, affordances, risks, and conflicts. Shaping our substrate for communication and collaboration through the lens of a position that will not acknowledge this new reality will, at best, yield us another barren and obsolete "iron cage" of a Weberian dystopia.

### 5. MANY ACTORS, ONE PRODUCT

Looking back at the brief narrative to appreciate the discontinuities inherent in a construction workflow, while putting contingencies in the forefront:

The owner decides on their needs, architect decides on the layout, this places a certain function in a certain position in relation with the environment prescribing the exposure of the volume in relation to the sun, in a different moment in time, the architect decides on the openings of this space based on requirements dictated by concerns of accessibility, facade systems, and architectural style. So, the solution for the space in which a given function will be hosted is bound by a series of conditions based on decisions made. Then an external agent, an acquaintance of the owner, recommends an interior designer. Through dynamics that go beyond our scope the owner is convinced.

The interior designer comes into play and must decide on the finish that is going to be applied. They have to rely on societal norms or evidence based research or their decisions, and these prescribe what communication tools they will use to convince the owner on the validity of their decisions (samples, swatches, rendering, etc.) a decision is reached, the contractor subcontracts the work to a team of painters

and they verify availability of the finishes and so forth.

Each solution is contingent on a series of decisions that are formalized in varying degrees, resolutions, and contexts. All the while, each actor is bent on refining their involvement and successful delivery from their own perspective. These relationships have been formalized in various diagrams and workflow languages that facilitate information flow and role distribution. These tools can be ad hoc, informal, or studied and carefully programmed using tools from Process Modeling domain, such as UML or BPMN. Their validation and semantic execution capabilities are due to their directed network structure. These latter are rigorous methods of planning that support validation and unequivocal communication. Yet at the end of the process, they are lost, once a specialist retires, and their experience and knowledge in having encountered different conflicts is pulled out of the common toolbox (Wong et al. 2000). Opening our cognitive or computing models to informal practices that can be formalized under one schema can yield better capabilities for parsing and searching that will permit benefiting from better affordances and can be used to automate process optimization efforts (Kitchin 1994).

It is important to note that a trend among AEC software providers on the other hand has been that of moving BIM applications onto the cloud for purposes of data mining, or data sniffing. These metrics, and the knowledge that they are collecting and using, are sold back to the project owner as a service, or third parties as industrial insight. All this naturally happens behind the private software suite interface, within the company, and with methods not necessarily published.

### CONCLUSION

As stated, finding a common language between actors or even different operations by a given actor is not easy to develop. This is due to the differing nature, temporal and spatial distribution of agents, tools, and environments in which fabrication, logistics, and assembly operations take place. The first research gap that is identified in a systematic review of 259 papers regarding multi agent BIM projects for infrastructure is in line with our proposal of developing a rich connected information substrate:

"[...] a growing use of ontologies, linked data techniques, and big data style approaches are reducing the need for stringent, structured data formats, weaving together data using graph based approaches processed via reasoning, rule engines and machine learning" (Bradley et al. 2016).

Their indication of a downside for this approach is a result of the lack of information and computer science knowledge within the AEC community (NB:



according to them AECOO: Architecture, Engineering, Construction, Owner, and Operator is the industry subset directly dependent on BIM). Our understanding is that, while this condition holds true, it is partially due to the disconnect with the analytical methods hidden behind the software's user interface. This lack can be exemplified in Bresenham's algorithm (or Wu's algorithm), solving a raster result for an analytical line in the modeling space. The result is the designer or other specialist's only window into the operations happening "under-the-hood".

The designer or the technician involved in these processes resolves only one given aspect of the operation at a given time. The way we can make sense of this unfathomable amount of information is by introducing vagueness and abstraction. In the same way the vantage point around an assemblage can change our perspective by letting parameters that are not critical to the problem, ebb and flow into focus, we can make sense of temporal roles and progress in the definition of a solution.

Research into implementing mechanisms of human cognition in a BIM setting is emerging. Work on visualization of vagueness in Multi-LOD (Level of Development) BIM (Abualdenien and Borrmann 2019) opens another way of virtualizing the chunking of the information for the benefit of clarity of scope in design problem solving. Mimicking the design communication methods of a traditional setting is one example of how one can start chiseling at the monolithic and prescriptive nature of today's building design.

Within this context, affordances are entities that satisfy actor or process needs and hidden affordances

are parameters that lie in proximity to the network, but in a different domain or cluster. Having the semantics of these entities searchable would yield unprecedented opportunities in resource sharing while being able to limit case searches to spatial proximities as previously mentioned. Graph structures are also well suited to defining optimized scheduling or to serializing design automation, reducing the need for specialist intervention in repetitive tasks.

The explicit representation of all entities and parameters in a networked manner will most definitely resolve the problems of compartmentalization, data loss, and repeat derivations within today's AEC workflows. Once established proofs of concept for project-wide graph processing are established, the pitfalls of expanding the knowledge base wider than previously attempted need to be identified.

Semantic Web applications for derived cross domain layers in BIMs are a promising prospect. There are still no standardized GDB solutions for BIM standards. Although graph applications and Free and Open Source Software (FOSS) BIM topics are entering the literature, there are no implementations or experiments that reach a substantial user base (Ismail et al. 2018; Logothetis et al. 2018). ifcOWL is a promising concept for rigorous and standardized semantic interoperability applications for data derivation, and there are already applications for cross domain information retrieval (Petrova et al. 2019). Today's technology can also support localized GDBs that would be able to open the door for cross domain automation and optimization, at the reach of the participants of the design, construction, and living processes.

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